**Title: Measurement of the head impacts in a sub-elite Australian Rules football team with an instrumented patch: An exploratory analysis**

**Running title:** Impacts in sub-elite ARF players

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**Abstract**

To investigate the frequency, magnitude and distribution of head impacts in Australian Football League players over a season of matches. A prospective cohort analysis of impact magnitude, frequency and distribution on data collected with a wireless head impact sensor worn behind the ear of 23 players. A total of 4,903 impacts were recorded. Players experienced on average 407 ±143 impacts over the duration of the study resulting in 30 ±38 impacts per-player per-match. Linear accelerations ranged from 10*g* to 153*g* with a mean, median and 95th percentile value of 17*g*, 13*g* and 40*g* respectively. Rotational accelerations ranged from 130 rad/s2 to 21,890 rad/s2 with a mean, median and 95th percentile value of 2,426 rad/s2, 1,556 rad/s2 and 7,571 rad/s2 respectively. This study obtained initial measurements on the frequency, magnitude, distribution and risk weighted exposure of head impacts in Australia Rules Football in order to better inform medical personnel in the identification and evaluation of at-risk players for concussion. The location of impacts varied considerably with the back of the head recording more total impacts than the front, side and top. Midfielders sustained more impacts per-player, per-match, and had higher median resultant linear accelerations than forwards and defenders. The results of this study, in which most impacts were within the low severity limit for linear, rotational, HITSP and RWECP, indicate that ARF needs to include more encompassing methods of examination of player exposure.

**Key words:** Head impact biomechanics, Instrumented patch, linear acceleration, rotational acceleration, Australian Football league

**Introduction**

As the most popular football code in Australia,[1](#_ENREF_1" \o "Gray, 2010 #3761) Australian Rules Football (ARF) is a full-contact, invasion game[2](#_ENREF_2" \o "Orchard, 1998 #2369) that generally involves less collisions and tackling than rugby union or rugby league. Similar to football (soccer) in the objectives of the game, ARF is a dynamic running game combining athleticism with speed, necessitating skillful foot and hand passing.[1](#_ENREF_1" \o "Gray, 2010 #3761), [3](#_ENREF_3" \o "Robertson, 2015 #3762) Unlike soccer, ARF involves aggressive tackling with sudden collisions between players and the ground.[2](#_ENREF_2" \o "Orchard, 1998 #2369), [4](#_ENREF_4" \o "Hrysomallis, 2006 #3825) There are 18 players on field, per team, during match activities, with up to four players utilized as interchange players.[5](#_ENREF_5" \o "Orchard, 2002 #54) The interchange players can be rotated onto the field as frequently as the coach requires. Players partake in ARF in one of three positional groups, forwards, midfielders, and defenders.[1](#_ENREF_1" \o "Gray, 2010 #3761) Forwards typically mark the ball (catch the ball on the full from a kick greater than 15 m) in the best position possible then take a free kick at the goals; midfielders typically work alongside forwards and defenders picking up loose balls from the ground or regaining possession and clearing the ball from their goal area; and defenders typically attempt to ‘spoil’ the opposition forwards marking the ball.[1](#_ENREF_1" \o "Gray, 2010 #3761)

Playing ARF involves activities such as running, kicking, frequent jumping/landing actions, and sudden changes in direction.[1](#_ENREF_1" \o "Gray, 2010 #3761), [6](#_ENREF_6" \o "Orchard, 2013 #3836) As a result of the fast paced nature of ARF, there is a high risk of injury.[7](#_ENREF_7" \o "Fortington, 2016 #3835) The most common match injuries, that occur to ARF players are muscle strains,[6](#_ENREF_6" \o "Orchard, 2013 #3836), [8-11](#_ENREF_8" \o "Stevenson, 2000 #225) joint or ligament sprains,[6](#_ENREF_6" \o "Orchard, 2013 #3836), [8-11](#_ENREF_8" \o "Stevenson, 2000 #225) contusions or haematomas[6](#_ENREF_6" \o "Orchard, 2013 #3836), [8](#_ENREF_8" \o "Stevenson, 2000 #225), [9](#_ENREF_9" \o "McManus, 2004 #3833), [11](#_ENREF_11" \o "Hrysomallis, 2013 #3837) and concussions.[11](#_ENREF_11" \o "Hrysomallis, 2013 #3837) Ranked as the fourth most common injury (4.3%) in community (under 18) ARF players,[2](#_ENREF_2" \o "Orchard, 1998 #2369), [11](#_ENREF_11" \o "Hrysomallis, 2013 #3837) the incidence of concussion is reported to have increased.[12](#_ENREF_12" \o "Finch, 2013 #3838) The incidence of concussion at the professional level of participation, the Australian Football League (AFL), is reported to be 5 to 6 per 1,000 player hours making this one of the most common injuries that occur during match participation.[11](#_ENREF_11" \o "Hrysomallis, 2013 #3837) As a result of the increase in sports-related concussions occurring, these injuries have become an increasingly serious concern.[13-15](#_ENREF_13" \o "Covassin, 2012 #2739)

As a subset of mild traumatic brain injuries[16](#_ENREF_16" \o "McCrory, 2013 #3184) information relating to the cause, course, and sequelae of concussion has increased. As a result of this information the knowledge surrounding the recognition and management of concussion has also improved.[17](#_ENREF_17" \o "Fortington, 2015 #3840) This is important in sports such as ARF where collisions can result in concussion.[17](#_ENREF_17" \o "Fortington, 2015 #3840) Furthermore there is a concern for the immediate, and long-term, effects of players involved in sports such as ARF and rugby that are subjected to repeated impacts to the head resulting in sub-concussive impacts occurring,[18](#_ENREF_18" \o "Baugh, 2012 #2666), [19](#_ENREF_19" \o "Gavett, 2011 #2556) and how these may adversely affect cerebral functions.[18-20](#_ENREF_18" \o "Baugh, 2012 #2666) As a result research into head impacts,[21](#_ENREF_21" \o "King, 2015 #3616) and prevention strategies such as body-contact/tackling skills[17](#_ENREF_17" \o "Fortington, 2015 #3840) have increased over the years, leading to greater insight into the likely causes and the longitudinal effects of these injuries.

Research has sought to better define the resultant linear and rotational accelerations that are involved in concussion injuries to the head through the use of telemetry, or impact sensors.[21-23](#_ENREF_21" \o "King, 2015 #3616) These impact sensors (gyroscopes/accelerometers) have been utilized in helmeted, and non-helmeted, sports to understand the link between the biomechanics of the head impact and the clinical outcomes of concussion in athletes.[21-28](#_ENREF_21" \o "King, 2015 #3616) Of the non-helmeted sports, soccer[29](#_ENREF_29" \o "Hanlon, 2012 #2460) and rugby union[21](#_ENREF_21" \o "King, 2015 #3616) have started to accumulate impact sensor data. Using this emerging technology to gain real-time data[26](#_ENREF_26" \o "Crisco, 2010 #2492), [30-33](#_ENREF_30" \o "Guskiewicz, 2011 #2163) on sports collisions, along with the mandatory use of helmets in American football, has afforded the systematic analysis of injury biomechanics that occur in match and training activities. This new technology has led to a more extensive knowledge of the magnitudes, distribution and frequency of accelerations involved in head injuries, that can be applied to football or any other circumstances where repetitive head injury can occur.

However, this technology has not been incorporated in ARF concussion research and management. The aim of this exploratory study was to investigate the head impact acceleration characteristics with the use of wireless head impact sensors during 12 matches in adult sub-elite level ARF players. This is the first study to embark on this emerging area of research within ARF. The generation of new knowledge may result in comparisons being drawn between player positions to identify injury risk and incidence within the sport.

**Methods**

A prospective observational cohort study was conducted on a single West Australian Football League (WAFL) sub-elite (reserves) team competing in the senior WAFL competition during the 2015 competition. All members of the team were invited to participate in the study. A total of twenty-threeplayers (21.0 ±2.4yr, 182.0 ±8.3cm and 77.6 ±6.5 kg) agreed to participate and were enrolled in the study. These players consisted of seven forwards; 11 midfielders and five defenders. Consent was obtained from the players before enrolling in the study. The researchers’ University ethics committee approved all procedures (MUHREC 2015/061). Approval was provided by the Western Australian Football Commission, participating team and players prior to commencing the study.

Study participants wore the XPatch impact-sensing skin patch (X2Biosystems Ltd, Seattle, Washington. United States of America; www.x2biosystems.com) on the skin covering their mastoid process (right side) during each match. The XPatch sensor sampling at 1,024 Hz was placed behind the player’s right ear just before they participated in match activities and was removed immediately after the match was completed. The positioning of the XPatch over the mastoid process is important to ensure that the sensor was not activated by enhanced soft-tissue effects when impacts occur.[34](#_ENREF_34" \o "Wu, 2015 #3753)

The XPatch contained a low-power, high-*g* triaxial accelerometer with 200*g* maximum per axis and a triaxial angular rate gyroscope to capture six degrees of freedom for linear and rotational time history accelerations of the heads center of gravity for all impacts that occurred during match participation. The time history incorporated three axes (x, y, z) of acceleration and three axes of velocity. Standing in an upright position these planes describe the medial-lateral, anterior-posterior and vertical acceleration and deceleration.

If an accelerometer exceeded the predetermined 10*g* linear acceleration threshold, 100 milliseconds (ms) of data (10 ms pre-trigger and 90 ms post-trigger) from each accelerometer and gyroscope were recorded to the on-board memory for later downloading. This data acquisition limit was based on a review of data acquisition limits utilized in previously published studies.[21](#_ENREF_21" \o "King, 2015 #3616)

Following the match, the XPatch were removed from the player and the data downloaded to the Injury Management Software (IMS) (X2Biosystems). The IMS enabled the raw accelerometer data to be transformed to the head center of gravity by using a rigid-body transformation for linear acceleration and a 5-point stencil for rotational acceleration.[21](#_ENREF_21" \o "King, 2015 #3616), [34](#_ENREF_34" \o "Wu, 2015 #3753) The biomechanical measures of head impact severity consisted of impact duration (ms), linear acceleration (*g*), and rotational head acceleration (rad/s2) Resultant linear acceleration is the rate of change in velocity of the estimated center of gravity of the head attributable to an impact and the associated direction of motion of the head.[35](#_ENREF_35" \o "Mihalik, 2010 #3259) Resultant rotational acceleration is the rate of change in rotational velocity of the head attributable to an impact, and its direction in a coordinate system with the origin at the estimated center of gravity of the head.[35](#_ENREF_35" \o "Mihalik, 2010 #3259) False impacts were removed by the X2Biosystems proprietary ‘de-clacking’ algorithm[21](#_ENREF_21" \o "King, 2015 #3616) by comparing the waveform of each impact to a ‘Gaussian-like’ reference waveform using cross-correlation.[21](#_ENREF_21" \o "King, 2015 #3616) Impacts with a resultant linear acceleration of <10*g* were removed. The remaining impacts were downloaded to an Excel spreadsheet and time-filtered to include only those impacts that occurred during match participation.

Head impact exposure including frequency, magnitude and location of impacts were quantified using previously established methods.[26](#_ENREF_26" \o "Crisco, 2010 #2492), [36](#_ENREF_36" \o "Crisco, 2011 #2601) Three measures of impact frequency were computed for each player: *player impacts*, the total, median 25th-75th interquartile range (IQR)], and the 95th percentile of head impacts recorded for a player during all the matches observed, *player group impacts*, the total, median [IQR], and the 95th percentile of impacts recorded for each of the player groups (forwards, midfielders and backs) during all matches observed, and *impacts per match*, the total, median [IQR], and the 95th percentile of head impacts recorded for a player during all the matches observed.

All filtered data on the Microsoft Excel spreadsheet was analyzed with SPSS V.22.0.0. The impact variables were not normally distributed (Kolmogorov-Smirnov; *p*<0.001). Therefore data were expressed as median [IQR], and as severity measures (95th percentile linear acceleration, 95th percentile rotational acceleration)[37](#_ENREF_37" \o "Hopkins, 2009 #1146), [38](#_ENREF_38" \o "Hopkins, 2007 #895) The impact location variables were computed as azimuth and elevation angles relative to the center of gravity (CG) of the head centered on the mid-sagittal plane.[39](#_ENREF_39" \o "Crisco, 2004 #3561) These were categorized as front (Left: θ = 180° to -135°; Right: θ = 180° to 135°), side (Left: θ =–135° to -45°; Right: θ =135° to 45°), back (Left: θ =-45° to 0°: Right: θ =45° to 0°) and top (Left: θ =180° through negative θ to 0°; Right: θ = 180° through positive θ to 0°) . Impacts to the top of the head were defined as all impacts above an α of 65° from a horizontal plane through the CG of the head.[40](#_ENREF_40" \o "Greenwald, 2008 #1809) Impact locations were analyzed by front, back, side and top impacts using a Friedman repeated measures ANOVA on ranks.

Head impacts were assessed by injury tolerance level for a concussion using previously published injury tolerance levels[31](#_ENREF_31" \o "Guskiewicz, 2007 #2494), [32](#_ENREF_32" \o "Broglio, 2010 #2605), [41](#_ENREF_41" \o "Broglio, 2011 #2527) for linear (>95*g*) and rotational acceleration (>5,500 rad/s2). Head impacts were assessed for impact severity using previously published levels for linear acceleration (mild <66*g*, moderate 66-106*g*, severe >106*g*) and rotational acceleration (mild <4,600 rad/s2, moderate 4,600-7,900 rad/s2, severe >7,900 rad/s2).[42-44](#_ENREF_42" \o "Harpham, 2013 #3267)

Two additional risk equations were included in the analysis of the impact data to identify players at risk of a concussion. The Head Impact Telemetry Severity Profile (HITSP)[40](#_ENREF_40" \o "Greenwald, 2008 #1809) is weighted composite score including linear and rotational accelerations, impact duration, as well as impact location. The Risk Weighted Exposure Combined Probability (RWECP)[45](#_ENREF_45" \o "Urban, 2013 #3261) is a logistic regression equation and regression coefficient of injury risk prediction of an injury occurring based on previously published analytical risk functions. The RWECP combines the resultant linear and rotational accelerations to elucidate individual player and team-based exposure to head impacts. As a value of 63 is a 75% indicator for a concussive injury[40](#_ENREF_40" \o "Greenwald, 2008 #1809), [46](#_ENREF_46" \o "Broglio, 2011 #2553) the HITSP values were evaluated by limits of less than 25% risk (<21), 25% to 75% risk (21-63) and >75% risk (>63). The RWECP values were also evaluated by the same values of 25% risk (<0.2500) 25% to 75% risk (0.2500-0.7500) and >75% risk (>0.7500).

The impact data was further assessed by grouping the resultant impacts by player age, height and body mass. As there were only 23 players enrolled in the study, this was undertaken by dividing the players into three groups based on player age, height and body mass distribution. These were termed lower (age: < 20 yr.; height <1.76 m; body mass: < 74 kg) middle (age: 20-21 yr.; height: 1.76-1.87 m; body mass: 74-78 kg) and higher (age: > 21 yr.; height >1.87 m; body mass: >78 kg). The resultant linear and rotational accelerations, HITSP and RWECP were analyzed using a Friedman repeated measures ANOVA on ranks. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied.

The HITSP and RWECP were analyzed by total, forwards, backs and midfielders recorded head impacts using a Friedman repeated measures ANOVA on ranks. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied. A one sample chi-squared (*χ2*) test and risk ratio (RR) with 95% confidence intervals (CI) were used to determine head impact risk. Statistical significance was set at *p*<0.05. .

**Results**

Throughout the course of the project, 12 matches and 23 players were monitored. For analysis, players were separated into three positional groups: forwards (n=7); midfielders (n=11); and defenders (n=5). Over the duration of the study 4,903 impacts were recorded. Players experienced on average 213 ±315 impacts per-player over the 12 matches resulting in 29 ±37 impacts per-player per-match. Linear accelerations ranged from 10*g* to 153*g* with a mean, median and 95th percentile value of 17*g*, 13*g* and 40*g* respectively. Rotational accelerations ranged from 130 rad/s2 to 21,890 rad/s2 with a mean, median and 95th percentile value of 2,426 rad/s2, 1,556 rad/s2 and 7,571 rad/s2 respectively (see Table 1).

The results for forwards, midfielders and defenders (see Table 1) revealed midfielders experience significantly more impacts per player, per match (36 +49) than forwards (RR: 4.1 [95% CI: 3.8 to 4.4]; *p*<0.0001) and defenders (RR: 3.1 [95% CI: 2.9 to 3.3]; *p*<0.0001). Forwards recorded higher resultant median rotational accelerations (1,764 [1,092 to 2,898] rad/s2) than defenders (*p*=0.8742) and midfielders (*p*=0.2235).

The number of impacts to the head varied over the season (see Table 2). The back of the head recorded more total impacts (n=2,466) than the front (RR: 3.7 [95% CI: 3.4 to 4.0]; *p*<0.0001), side (RR: 1.5 [95% CI: 1.4 to 1.6] *p*<0.0001) and top (RR: 26.8 [95% CI: 21.9 to 33.0]; *p*<0.0001) of the head. The top of the head recorded the highest median resultant linear acceleration (18 [13 to 26] *g*) when compared with impacts recorded to the front (*p*=0.8993), side (*p*<0.0001) and back (*p*<0.0001) of the head. Forwards recorded a higher median resultant linear acceleration (22 [18 to 48] *g*) to the top of the head than midfielders (*p*=0.0280) and defenders (*p*=0.1282). The front of the head recorded the highest resultant median rotational accelerations (3,186 [2,072 to 5,408] rad/s2) when compared with the back (*p*<0.0001), side (*p*<0.0001) and top (*p*=0.0987) of the head. Forwards recorded the highest resultant median rotational accelerations to the top of the head (7,560 [2,531 to 10,556] rad/s2) when compared with midfielders (*p*=0.0180) and defenders (*p*=0.0280). The front of the head recorded the highest median HITSP (19 [16 to 27]) and RWECP (0.0013 [0.0004 to 0.0104]) over the duration of the study. Forwards recorded the highest median HITSP (26 [18-49]) and RWECP (0.5400 [0.0007-0.6458]) to the top of the head when compared with midfielders (*p*=0.0180; *p*=0.0277) and defenders (*p*=0.0425; *p*=0.0425) over the duration of the study.

There were 14 (0.3%) impacts recorded above the linear injury risk limit and 436 (8.9%) impacts above the rotational injury risk limit (see Table 3). Midfielders recorded more impacts in the injury risk limit for rotational accelerations (>5,500 rad/s2) than forwards (*p*=0.7111) and defenders (*p*=0.0278) over the duration of the study. Defenders recorded more impacts (6.7%) above the severe rotational acceleration (>7,900 rad/s2) threshold than midfielders (*p*=0.0009) and forwards (*p*=0.0461). The majority of the impacts were in the low impact severity limit for linear (98.8%), rotational (88.3%), HITSP (80.7%) and RWECP (96.2%) data acquisition limits.

There were statistically significant differences observed for the resultant linear (*χ2*(2)=10.39; *p*=0.0055), rotational (*χ2*(2)=21.44; *p*<0.0001), HITSP (*χ2*(2)=24.64; *p*<0.0001), and RWECP (*χ2*(2)=25.04; *p*<0.0001) when comparing impacts for the lower, middle and higher age groups (see Table 4). The was a statistically significant difference observed on post hoc analysis that the lower age group recorded a higher median result when compared the middle age group for resultant linear (14 *g* vs. 13 *g*; z=-2.82; *p*=0.0048) and rotational (1,863 rad/s2 vs. 1,519; z=-3.67; *p*=0.0002) accelerations; RWECP (0.0003 vs. 0.0002; z=-3.89; *p*=0.0001) and the middle and higher age group for HITSP (19 vs. 20; z=-2.98; *p*=0.0029).

**Discussion**

This study reports, for the first time, the head impact biomechanics experienced whilst participating in ARF league matches. From this data, the magnitude, distribution, frequency and severity of impacts to the head experienced by participants during ARF match play can be characterized. The primary aim of this study was to quantify the frequency, magnitude and location of head impacts over the course of a football season and then compare the results between player position and to similar codes such as in junior, high school and college American football players and senior amateur rugby union rugby and American football.

This is the first study to record and report the magnitude, frequency and distribution of impacts to the head for players participating in ARF During the study, there was an average of 213 ±3156 impacts per-player for the season recorded for ARF players resulting in 29 ± 37 impacts per-player per-match. This is less than the impacts recorded in senior amateur rugby union[21](#_ENREF_21" \o "King, 2015 #3616) (564 + 618 per-player for the season; 95 + 133 impacts per-player, per-match) and collegiate level American football, (950[30](#_ENREF_30" \o "Guskiewicz, 2011 #2163) impacts per-athlete, per season to 1,353[47](#_ENREF_47" \o "Schnebel, 2007 #3264) impacts per-athlete (practice and games combined) exposure).

Most of the impacts recorded over the duration of the study were in the low impact severity limit for resultant linear (<66*g*: 98%) and rotational (<4,500 rad/s2: 88%) accelerations; HITSP (<21: 80%) and RWECP (<0.2500: 96%) and only a small percentage (0.3%) of impacts were above the resultant linear (>95*g*: 0.3%) and rotational (>5,500 rad/s2: 8.9%) injury tolerance limits. Despite the lower number of impacts above the injury tolerance levels for all the measures reported, there is the risk that the high percentage of impacts recorded below these limits may be sub-concussive and have long-term cumulative effects.[54](#_ENREF_54" \o "Broglio, 2012 #2911), [55](#_ENREF_55" \o "Stern, 2011 #2677) The minimum level of impact acceleration to produce a non-structural brain injury, with neuronal changes is yet to be established.[18](#_ENREF_18" \o "Baugh, 2012 #2666) Also, these neuronal changes may not result in any apparent clinical symptoms[18](#_ENREF_18" \o "Baugh, 2012 #2666) but, may be sufficient to initiate neuro-degeneration resulting in long-term neurocognitive complications.[18](#_ENREF_18" \o "Baugh, 2012 #2666), [19](#_ENREF_19" \o "Gavett, 2011 #2556) This is a concern as it has been reported[20](#_ENREF_20" \o "Gysland, 2012 #2586) that these impacts do not represent clinically meaningful changes from preseason to postseason on concussion tests often used to identify neurologic impairment such as the Automated Neuropsychological Assessment Metrics (ANAM),[56](#_ENREF_56" \o "Cernich, 2007 #3843) the Standardized Assessment of Concussion (SAC),[57](#_ENREF_57" \o "McCrea, 2001 #2176) the Balance Error Scoring System (BESS),[58](#_ENREF_58" \o "Riemann, 1999 #3844) the Sensory Organization test (SOT)[59](#_ENREF_59" \o "Broglio, 2008 #3845) and the Graded Symptom Checklist.[60](#_ENREF_60" \o "Grubenhoff, 2010 #2652)

Although inter-code comparisons may not offer clarity, the key is attaining more knowledge in relationship to the impact frequency, magnitude and the relationship to observable, and unobservable, concussion signs and symptoms and resultant neuro-degenerative changes. Impacts that do not result in any overt clinical symptoms of concussion,[65](#_ENREF_65" \o "Giza, 2013 #3235) classified as sub-concussive impacts, may have a long-term cumulative effects.[20](#_ENREF_20" \o "Gysland, 2012 #2586) Furthermore, the results of this study, in which most impacts were within the low severity limit for linear, rotational, HITSP and RWECP, indicate that ARF needs to include more encompassing methods of examination of player exposure. It has been reported that concussive injuries occur, on average, between 98*g*[66](#_ENREF_66" \o "Rowson, 2012 #2502) to 104*g* for resultant linear accelerations, and 4,726[66](#_ENREF_66" \o "Rowson, 2012 #2502) and 6,432[52](#_ENREF_52" \o "Pellman, 2003 #2585) rad/s2 for resultant rotational accelerations. In terms of sub-concussive impacts, previous studies[52](#_ENREF_52" \o "Pellman, 2003 #2585), [66](#_ENREF_66" \o "Rowson, 2012 #2502) have reported that these can occur between 26*g*[66](#_ENREF_66" \o "Rowson, 2012 #2502) to 57*g*,[52](#_ENREF_52" \o "Pellman, 2003 #2585) for resultant linear accelerations and 1,230[66](#_ENREF_66" \o "Rowson, 2012 #2502) and 4,028[52](#_ENREF_52" \o "Pellman, 2003 #2585) rad/s2 for resultant rotational accelerations. Research[67](#_ENREF_67" \o "Beckwith, 2013 #3118) shows that participants with a delayed diagnosis of concussion, although moderately associated with high kinematic measures, had an increased number of low kinematic measures. In the present study the mean resultant linear (17*g*) and rotational (2,426 rad/s2) accelerations recorded over the season of matches places ARF values less than those in senior amateur rugby union,[21](#_ENREF_21" \o "King, 2015 #3616) collegiate,[66](#_ENREF_66" \o "Rowson, 2012 #2502) and professional[52](#_ENREF_52" \o "Pellman, 2003 #2585) levels of American football participation.

Documenting impacts to the head is important because of the cumulative effects on the brain.[48](#_ENREF_48" \o "McKee, 2012 #3080) However, measuring linear and rotational accelerations provides even greater understanding of the potential damage of head impacts.[31](#_ENREF_31" \o "Guskiewicz, 2007 #2494), [32](#_ENREF_32" \o "Broglio, 2010 #2605), [41](#_ENREF_41" \o "Broglio, 2011 #2527), [49](#_ENREF_49" \o "Pellman, 2003 #2585) Additionally, and unique to this study, was the inclusion of a risk-weighted cumulative exposure (RWE) measure.[45](#_ENREF_45" \o "Urban, 2013 #3261) By adjusting the impacts’ contribution to cumulative exposure according to its associated impact tolerance, the RWE for linear, rotational, and a combined (linear and rotational) probability measure can be established.[45](#_ENREF_45" \o "Urban, 2013 #3261) In order to accurately predict the risk of concussion, both linear and rotational accelerations should be accounted for, to determine the concussion risk.[45](#_ENREF_45" \o "Urban, 2013 #3261) The RWE combined probability (RWECP) enabled this concussion risk prediction to be undertaken. By recording the RWECP of individual players, player groups, and for the sport[50](#_ENREF_50" \o "King, 2015 #3810) the resulting values may assist with the identification of players with a potential cumulative exposure resulting in concussion. Only one other study[45](#_ENREF_45" \o "Urban, 2013 #3261) has reported the RWECP and this was in High School level American Football. Utilizing the same logistic regression equations and regression coefficients, it can be seen that the median RWECP in High School level American football players was 0.497[45](#_ENREF_45" \o "Urban, 2013 #3261) and this was higher than the current study (0.0003) recorded on ARF players.

In the current study, the mean, median and 95th percentile value of the resultant linear (17 + 12*g*, 13*g* and 40*g*) and rotational accelerations (2,426 + 2,480 rad/s2, 1,556 rad/s2 and 7,571 rad/s2) were established. When compared with collegiate American football participation,[36](#_ENREF_36" \o "Crisco, 2011 #2601) the 95th percentile resultant linear (62*g*) acceleration was higher than the ARF players but the resultant rotational (4,378 rad/s2) acceleration were lower than ARF players. When compared with senior amateur rugby union[21](#_ENREF_21" \o "King, 2015 #3616) the mean resultant linear (22*g*) and rotational (3,903 rad/s2) accelerations were higher than those reported for the ARF players. Further research into the biomechanics of ARF match and training activities at all levels is warranted.

The location of impacts recorded in the current study varied considerably with the back of the head (50%) recording more total impacts than the front (14%), side (34%) and top (2%) of the head. However, the top of the head recorded the highest median resultant linear acceleration (18*g*) over the duration of the study. A possible reason for the top of the head having the highest resultant linear acceleration may be related to the type of match activities undertaken in ARF. As seen in Table 2, forwards and defenders recorded median linear accelerations of 22g and 20*g* respectively to the top of the head while midfielders recorded higher median linear accelerations (17*g*) to the front of the head. The roles of the forwards are to mark the ball and this is done by jumping or jostling against defenders and midfielders in an attempt to get the ball. In doing this defenders will be attempting to interfere with the forwards as they try to mark the ball and this can result in contact with the top of the head, knocking the player out of the way resulting in the forward and defender recording impacts to the top of the head or may fall onto the group resulting in the higher linear accelerations being recorded. In senior amateur rugby union,[21](#_ENREF_21" \o "King, 2015 #3616) impacts were more commonly recorded to the right (45%) side of the head while collegiate level American football up to 45% of impacts occurred to the front of the head.[27](#_ENREF_27" \o "Mihalik, 2007 #2461) The variations observed between the three comparative codes may stem from the differences in player formations, the protective equipment utilized and the rules of the sporting code in terms of match participation. Further research is warranted to evaluate the differences between the different sporting codes and to identify inter-code differences such as player-position groups.

Examining the results between player-positions identified that midfielders sustained more impacts (261) per-player, per-match, and recorded a higher median resultant linear acceleration (13*g*) than forwards and defenders. However, forwards recorded higher resultant median rotational accelerations (1,764 rad/s2) and this may be related to the different activities and roles that these players participate in through match participation. Despite these differences, defenders recorded a higher median HITSP (16) than midfielders and forwards and these may also be as a result of the differences in positional play during match activities. The variations observed between player-positions warrants further research to identify what match related activities result in these differences being observed. For example, while all players are able to be on any part of the field at any point in a game, they are normally assigned to a certain area for their role.[1](#_ENREF_1" \o "Gray, 2010 #3761) For example the center, in conjunction with two wingmen, are normally positioned in the midfield area of the oval.[1](#_ENREF_1" \o "Gray, 2010 #3761) The center normally attains the ball and links the defence and attack. In the forward area, a full forward [Forward category] is the main target for the ball when attacking.[1](#_ENREF_1" \o "Gray, 2010 #3761) The full forward must be strong at one-on-one contests to wrestle off opponents.[1](#_ENREF_1" \o "Gray, 2010 #3761) Due to the free-flowing and complex nature of each position, more data is required on each player in order to determine the level of risk associated with the number of impacts to the head.

An interesting finding in analyzing the impact data by age, height and body mass were the differences observed. Players in the lower age group (<20 yr.) had fewer average impacts per-player per-season but recorded higher median resultant linear and rotational accelerations but interestingly had a lower median HITSP and RWECP. When viewed by player height, players above 1.87 m recorded higher median resultant linear and rotational accelerations and as a result had a higher median HITSP and RWECP. When viewed by body mass players in the middle group recorded a higher median resultant linear and rotational accelerations and as a result had a higher median HITSP and RWECP. A possible reason for this finding is that players under the age of 20, over 1.87 m tall and with a body mass of 74-78 kg may be exposed to more severe impacts than other players. This may be as a result of less playing experience, playing in positions where their height would be an advantage strategically and have the body mass that enables the player to be exposed to positions on the field of play and record more impacts than other player positions. Further research is warranted exploring these aspects on a larger cohort in different sporting codes to identify if there is a similar pattern.

More knowledge on the frequency, magnitude, distribution and risk weighted exposure of head impacts may assist in the identification of high-risk events and better inform medical personnel of the need to evaluate a player for concussion.[51](#_ENREF_51" \o "Broglio, 2012 #2915), [52](#_ENREF_52" \o "Greenwald, 2012 #2665) It is a critical to understand the biomechanical basis for mild traumatic brain injuries (concussion injuries), correlating head impact exposure with the clinical variables associated with these injuries, and understanding the acute and long-term effect of repeated sub-concussive impacts.[36](#_ENREF_36" \o "Crisco, 2011 #2601)

***Limitations***

This study has several limitations which need to be considered when interpreting the results. The use of the X2Patch was novel in that the patch incorporates the accelerometer and gyroscope into a reusable monitor adhered to the side of the head behind the ear directly over the mastoid process of the player. The patches were applied utilizing an adhesive patch to hold the patch to the adhesive and this was applied to the side of the head behind the ear. It was important that the XPatch was applied directly over the mastoid process as the average estimated mass of the skin-patch system is greater than the mass of the sensor itself[34](#_ENREF_34" \o "Wu, 2015 #3753) and placement of the XPatch in a lower position may activate soft tissue in the neck during impacts providing false impacts and associated impact biomechanics. Additionally, the effects of sweating by the player, and some extreme weather conditions, resulted in some of the adhesives falling off the player during the match activities. As well, players who were grabbed around the head during the tackle sometimes had the patch pulled off. As a result the data reported was incomplete and the number of impacts would be more than have been reported.

Although the XPatch has undergone some reported validation studies, and been compared with the Head Impact Telemetry System (HITS), the results have varied. The accelerometers utilized in this study have been reported to have a strong correlation for anterior-posterior translation (r2=0.93)[34](#_ENREF_34" \o "Wu, 2015 #3753) a normalized root square error of 18% for peak linear acceleration (PLA) with an over-prediction of 15 ±7g and 2,500 ±1,200 rad/s2 for peak rotational accelerations (PRA).[34](#_ENREF_34" \o "Wu, 2015 #3753) It has also been reported[53](#_ENREF_53" \o "Nevins, 2015 #3754) that the XPatch had good estimates of PLA but underestimated PRA by more than 25% but recorded more impacts than were visibly seen. Although we found this data, there are no consistent reliability studies for the XPatch and the interpretation of these results should be interpreted with some caution.

Videotape analysis to enable verification of the impacts recorded and was not undertaken as there were not enough video-recorders to enable coverage of the complete field. The size of the field where ARF players participate in match activities was 155 m wide by 185 m long. There was no one position to stand where these who field was able to be covered with a video camera enabling verification of the impact to be undertaken post-match.

Csports some [54](#_ENREF_54" \o "Gastin, 2013 #3842)when compared with American football, rugby union and rugby league. Sports such as American Football, rugby union, rugby league and ARF are participated under different contact rules and utilize different participation activities. In addition to this, t.[55](#_ENREF_55" \o "Deutsch, 2007 #1123) Comparing position results to other codes is complex. For example, when an ARF player makes a tackle, they tend to travel at slightly faster velocities compared to the opposition player being tackled. In rugby union,[56](#_ENREF_56" \o "Quarrie, 2008 #1051) and rugby league,[57](#_ENREF_57" \o "King, 2012 #2606), [58](#_ENREF_58" \o "King, 2010 #3061) where lines of attackers and defenders face off, the ball carrier’s velocity prior to being tackled is relatively stable. The tackler, with a higher velocity entering the tackle, adjusts their relative velocity before making contact.[59](#_ENREF_59" \o "Hendricks, 2012 #2877) In American football, defensive and offensive linemen have the lowest head impact magnitudes of all player positions but the greatest number of head impacts recorded.[27](#_ENREF_27" \o "Mihalik, 2007 #2461), [32](#_ENREF_32" \o "Broglio, 2010 #2605), [47](#_ENREF_47" \o "Schnebel, 2007 #3264) Although comparisons between the different player positions of these different sporting codes may be complex, the value of this comparison is at the individual level, where the contribution of sub-concussive impacts may lead to impairment on clinical measures of neurologic function.[20](#_ENREF_20" \o "Gysland, 2012 #2586)

The current study only reports on 23 players in 12 matches and should not be suggestive of the frequency, magnitude and location of other levels of participation of ARF. This is seen as a limitation and further studies are recommended on a larger cohort of players. Only 12 matches were recorded during the 2015 domestic competition season. As a result, the findings of this study should not be seen as reflective of the average number of impacts, and their associated impact biomechanics, of a full competition season for ARF players.

**Conclusion**

For the first time, the head impact biomechanics experienced with participation in Australian Football league matches was measured. Using instrumented mastoid-based impact sensors (accelerometer) over the course of a single season 4,903 impacts were recorded. Players experienced 29 ±37 impacts per-player per-match with 14 impacts recorded above the linear injury risk limit, and 436 impacts about the rotational injury risk limit signifying that some impacts above the suggested 95*g* and 5500 rad/s2 are occurring. Although the majority of the impacts recorded were under the linear and rotational injury risk limits, the effects of the frequency and location of these impacts remains unknown. In comparison to senior amateur rugby union and American football players, players in this study were subjected to less overall, and high risk impacts, but the longitudinal effects of this remains unclear. However, inter-code comparisons are complex and the value of this comparison is at the individual level, where the contribution of sub-concussive impacts may lead to impairment on clinical measures of neurologic function. The key to this study was obtaining and thus gaining initial measurements on the frequency, magnitude, distribution and risk weighted exposure of head impacts in Australia Rule Football in order to assist in the identification at-risk players which will better inform medical personnel of the need to evaluate a player for concussion.

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**Compliance with Ethical Standards**

The authors declare that there are no competing interests associated with the research contained within this manuscript. No sources of funding were utilised in conducting this study. According to the definition given by the International Committee of Medical Journal Editors (ICMJE), the authors listed above qualify for authorship on the basis of making one or more of the substantial contributions to the intellectual content of the manuscript.

**Conflicts of interest**

Doug King, Mark Hecimovich, Trevor Clark and Conor Gissane declare that they have no conflict of interest.

**Tables**

**Table 1:** Impacts to the head greater than10*g* for total impacts recorded, impacts by forwards midfielders and defenders in an amateur Australian Football League team over a season of matches. Data are presented as mean and standard deviation (±SD), median [interquartile range] and 95th percentile for total impacts, impacts per player position group, impact duration (ms), resultant linear and rotational acceleration, head impact telemetry severity profile and risk weighted exposure combined probability

**Table 2:** Impacts to the head greater than 10*g* by impact location for total impacts, impacts recorded by forwards midfielders and defenders in an amateur Australian Football League team over a season of matches. Data are presented as mean (±SD), median [IQR] and 95th percentile for total impacts, impacts per player position group, impact duration (ms), resultant linear and rotational acceleration, head impact telemetry severity profile and risk weighted exposure combined probability.

**Table 3:** Impacts to the head greater than 10*g* by injury tolerance, injury severity for resultant linear and rotational accelerations, head impact telemetry severity profile and risk weighted exposure combined probability for total impacts, impacts recorded by forwards midfielders and defenders in an amateur Australian Football League team over a season of matches. Data are presented as number of impacts and percentage of impacts recorded.

**Table 4:** Impacts to the head greater than 10*g* by age, height and weight groups in an amateur Australian Football League team over a season of matches. Data are presented as mean (±SD), median [IQR] and 95th percentile for total impacts per player per-season, resultant linear and rotational acceleration, head impact telemetry severity profile and risk weighted exposure combined probability

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|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Total**  **Impacts** | **Per-player**  **per-match**  **season** | **Per-player**  **per-match** | **Impact**  **duration**  **(ms)** | **PLA (*g*)** | | | **PRA(rad/s2)** | | | **HITSP** | | | **RWECP** | | |
| **n=** | **Mean ±SD** | **Mean ±SD** | **Mean ±SD** | **Mean ±SD** | **Median [IQR]** | **95%** | **Mean ±SD** | **Median [IQR]** | **95%** | **Mean ±SD** | **Median [IQR]** | **95%** | **Mean ±SD** | **Median [IQR]** | **95%** |
| **Total** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 4,903 | 213 ±315 | 29 ±37 | 7.1 ±6.3 | 17 ±12 | 13 [11-18] | 40 | 2,426 ±2,480 | 1,556 [1,020-2,794] | 7,571 | 19 ±15 | 16 [14-19] | 39 | 0.0298 ±0.1404 | 0.0003 [0.0001-0.0009] | 0.9315 |
| **Forwards** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 764 | 109 ±105bc | 14 ±8bc | 6.5 ±5.8 | 17 ±13 | 10 [7-17] | 37 | 2,505 ±2,427 | 1,764 [1,092-2,898] | 7,292 | 19 ±16 | 16 [14-19] | 35 | 0.0287 ±0.1392 | 0.0003 [0.0002-0.0010] | 0.0681 |
| **Midfielder** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 3,131 | 261 ±417a | 36 ±49a | 7.0 ±6.3 | 17 ±11 | 13 [11-18] | 39 | 2,351 ±2,407 | 1,520 [1,018-2,655] | 7,155 | 19 ±15 | 16[14-19] | 39 | 0.0270 ±0.1338 | 0.0002 [0.0002-0.0008] | 0.0721 |
| **Defender** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 1,008 | 202 ±180a | 26 ±18a | 7.7 ±6.7 | 18 ±13 | 13 [11-18] | 44 | 2,623 ±2,738 | 1,553 [978-3,105] | 13,327 | 20 ±15 | 16 [14-20] | 44 | 0.0403 ±0.1621 | 0.0003 [0.0001-0.0012] | 0.3024 |

[IQR] = Interquartile (25th to 75th) percentile; 95% = 95th percentile; PLA (*g*) = peak linear acceleration in gravitational force (*g*); PRA (rad/s2) = peak rotational acceleration in radians/second2; HITSP = Head Impact Telemetry Severity Profile; RWECP = Risk Weighted Exposure Combined Probability; Significant difference (*p*<0.05) than (a) = Forward; (b) = Midfielder; (c) = Defender

**Table 2:** Impacts to the head greater than 10*g* by impact location for total impacts, impacts recorded by forwards midfielders and defenders in an amateur Australian Football League team over a season of matches. Data are presented as mean (±SD), median [IQR] and 95th percentile for total impacts, impacts per player position group, impact duration (ms), resultant linear and rotational acceleration, head impact telemetry severity profile and risk weighted exposure combined probability.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Impacts** | | | | **PLA (*g*)** | | | **PRA(rad/s2)** | | | **HITsp** | | | **RWE(CP)** | | |
| **Location** | **No.** | **%** | **duration (ms)** | **Mean ±SD** | **Median [IQR]** | **95%** | **Mean ±SD** | **Median [IQR]** | **95%** | **Mean ±SD** | **Median [IQR]** | **95%** | **Mean ±SD** | **Median [IQR]** | **95%** |
| **Total** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | Front | 672 | 13.7 | 10.5 ±8.2 | 23 ±17ef | 17 [13-27] | 57 | 4,257 ±3,322ef | 3,186 [2,072-5,408] | 11,078 | 26 ±23ef | 19 [16-27] | 61 | 0.0853 ±0.2285ef | 0.0013 [0.0004-0.0104] | 0.761 |
|  | Back | 2,466 | 50.3 | 6.3 ±5.7 | 16 ±10dfg | 12 [11-16] | 34 | 1,946 ±2,109dfg | 1,299 [896-2,069] | 5,564 | 18 ±13dfg | 15 [14-17] | 34 | 0.0195 ±0.1160dfg | 0.0002 [0.0001-0.0004] | 0.0163 |
|  | Side | 1,673 | 34.1 | 6.8 ±5.7 | 17 ±11deg | 13 [11-17] | 36 | 2,355 ±2,222deg | 1,633 [1,059-2,767] | 6,720 | 19 ±12deg | 16 [14-19] | 34 | 0.0220 ±0.1189deg | 0.0003 [0.0002-0.0008] | 0.486 |
|  | Top | 92 | 1.9 | 9.3 ±7.2 | 22 ±13ef | 18 [13-26] | 53 | 3,262 ±2,697ef | 2,216 [1,359-4,757] | 8,599 | 23 ±12ef | 19 [15-25] | 46 | 0.0439 ±0.1613ef | 0.0007 [0.0002-0.0061] | 0.4181 |
| **Forwards** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | Front | 119 | 15.6 | 9.9 ±7.6 | 23 ±18befg | 17 [13-27] | 61 | 4,100 ±3,085ef | 3,252 [2,179-4,435] | 10,389 | 25 ±21ef | 19 [16-27] | 60 | 0.0741 ±0.2091ef | 0.0012 [0.0004-0.0058] | 0.6602 |
|  | Back | 334 | 43.7 | 5.2 ±4.8 | 15 ±11bdfg | 12 [11-15] | 27 | 1,962 ±2,13dfg | 1,334 [896-2,144] | 6,086 | 18 ±14bdfg | 15 [14-17] | 26 | 0.0198 ±0.1215dfg | 0.0002 [0.0001-0.0004] | 0.0202 |
|  | Side | 304 | 39.8 | 6.5 ±5.4 | 16 ±11de | 13 [11-17] | 31 | 2,370 ±1,979deg | 1,800 [1,162-2,850] | 6,066 | 19 ±15deg | 16 [15-19] | 30 | 0.0152 ±0.1006deg | 0.0003 [0.0002-0.0009] | 0.0206 |
|  | Top | 7 | 0.9 | 11.4 ±8.6 | 32 ±21bde | 22 [18-48] | \* | 7,189 ±4,342bcef | 7,560 [2,531-10,556] | \* | 35 ±22bcef | 26 [18-49] | \* | 0.2635 ±0.3927bcef | 0.5400 [0.0007-0.6458] | \* |
| **Midfielders** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | Front | 393 | 12.6 | 11.0 ±8.6 | 23 ±16aef | 17 [13-27] | 58 | 4,353 ±3,418ef | 3,335 [2,069-5,505] | 11,652 | 27 ±25ef | 20 [16-27] | 68 | 0.0893 ±0.2389ef | 0.0015 [0.0004-0.0123] | 0.8422 |
|  | Back | 1,656 | 52.9 | 6.4 ±5.8 | 16 ±9ad | 13 [11-16] | 34 | 1,889 ±1,938dfg | 1,315 [926-2,073] | 5,124 | 18 ±12adfg | 15 [14-18] | 34 | 0.0151 ±0.0992dfg | 0.0002 [0.0001-0.0004] | 0.0121 |
|  | Side | 1,013 | 32.4 | 6.5 ±5.3 | 17 ±11d | 13 [11-17] | 36 | 2,296 ±2,228de | 1,556 [1,043-2,629] | 6,867 | 19 ±13deg | 15 [14-18] | 34 | 0.0223 ±0.1197de | 0.0003 [0.0002-0.0462] | 0.0462 |
|  | Top | 69 | 2.2 | 9.2 ±7.3 | 21 ±12a | 16 [12-23] | 54 | 2,845 ±2,322ace | 1,958 [1,148-4,219] | 8,009 | 22 ±11acef | 18 [15-24] | 44 | 0.0296 ±0.1253ace | 0.0004 [0.0002-0.0044] | 0.2408 |
| **Defenders** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | Front | 160 | 15.9 | 9.6 ±7.7 | 22 ±16ef | 17 [12-27] | 56 | 4,120 ±3,231ef | 2,947 [1,954-5,267] | 10,802 | 25 ±20ef | 19 [16-27] | 59 | 0.0820 ±0.2141ef | 0.0009 [0.0004-0.0096] | 0.7104 |
|  | Back | 476 | 47.2 | 6.6 ±5.9 | 16 ±12df | 12 [11-15] | 40 | 2,154 ±2,621dfg | 1,214 [820-2,230] | 8,378 | 18 ±13df | 15 [14-17] | 41 | 0.0353 ±0.1585df | 0.0002 [0.0001-0.0005] | 0.1818 |
|  | Side | 356 | 35.3 | 8.2 ±6.9 | 18 ±13de | 13 [11-19] | 45 | 2,545 ±2,428de | 1,714 [1,053-3,138] | 7,711 | 20 ±14de | 16 [14-20] | 39 | 0.0297 ±0.1394de | 0.0003 [0.0002-0.0013] | 0.088 |
|  | Top | 16 | 1.6 | 8.7 ±6.2 | 21 ±9 | 20 [14-30] | \* | 3,346 ±2,031abe | 2,554 [1,668-5,385] | \* | 22 ±7ab | 19 [16-26] | \* | 0.0091 ±0.0171ab | 0.0008 [0.0004-0.0146] | \* |

[IQR] = Interquartile (25th to 75th) percentile; 95% = 95th percentile; PLA (*g*) = peak linear acceleration in gravitational force (*g*); PRA (rad/s2) = peak rotational acceleration in radians/second2; HITSP = Head Impact Telemetry Severity Profile; RWECP = Risk Weighted Exposure Combined Probability; \* = not able to be calculated; Significant difference (*p*<0.05) than (a) = Forward; (b) = Midfielder; (c) = Defender; (d) = Front; (e) = Back; (f) = Side; (g) = top

**Table 3:** Impacts to the head greater than 10*g* by injury tolerance, injury severity for resultant linear and rotational accelerations, head impact telemetry severity profile and risk weighted exposure combined probability for total impacts, impacts recorded by forwards midfielders and defenders in an amateur Australian Football League team over a season of matches. Data are presented as number of impacts and percentage of impacts recorded.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **Total** | **Forwards** | **Midfielders** | **Defenders** |
|  |  |  | **n= (%)** | **n= (%)** | **n= (%)** | **n= (%)** |
| **Injury Tolerance** | | | | | | |
|  | Linear | >95*g* | 14 (0.3) | 4 (0.5) | 7 (0.2) | 3 (0.3) |
|  | Rotational | >5,500 rad/s2 | 436 (8.9) | 67 (8.8) | 261 (8.3)c | 108 (10.7)b |
| **Injury Severity (Linear)** | | | | | | |
|  | Mild | <66*g* | 4,282 (98.8) | 753 (98.7) | 3,098 (98.9) | 991 (98.3) |
|  | Moderate | 66-106*g* | 52 (1.1) | 10 (1.3) | 26 (0.8)c | 16 (1.6)b |
|  | Severe | >106*g* | 9 (0.2) | 2 (0.3) | 6 (0.2) | 1 (0.1) |
| **Injury Severity (Rotational)** | | | | | | |
|  | Mild | <4,600 rad/s2 | 4,238 (88.3) | 673 (88.1) | 2,795 (89.3) | 860 (85.3) |
|  | Moderate | 4,600-7,900 rad/s2 | 344 (7.0) | 57 (7.5) | 207 (6.6) | 80 (7.9) |
|  | Severe | >7,900 rad/s2 | 231 (4.7) | 34 (4.5)c | 129 (4.1)c | 68 (6.7)ab |
| **Head Impact Telemetry severity profile (HITSP)** | | | | | | |
|  | Mild | <21 | 3,958 (80.7) | 624 (81.7) | 2,543 (81.2) | 791 (78.5) |
|  | Moderate | 21-63 | 863 (17.6) | 128 (16.8) | 536 (17.1) | 199 (19.7) |
|  | Severe | >63 | 82 (1.7) | 12 (1.6) | 52 (1.7) | 18 (1.8) |
| **Risk Weighted Exposure combined probability (RWECP)** | | | | | | |
|  | Mild | <0.2500 | 4,719 (96.2) | 736 (96.3) | 3,029 (96.7) | 954 (94.6) |
|  | Moderate | 0.2500-0.7500 | 96 (2.0) | 14 (1.8) | 51 (1.6)c | 31 (3.1)b |
|  | Severe | >0.7500 | 88 (1.8 | 14 (1.8) | 51 (1.6) | 23 (2.3) |



rad/s2 = radians/second2; HITSP = Head Impact Telemetry Severity Profile; RWECP = Risk Weighted Exposure Combined Probability; Significant difference (*p*<0.05) than (a) = Forward; (b) = Midfielder; (c) = Defender

**Table 4:** Impacts to the head greater than 10*g* by age, height and weight groups in an amateur Australian Football League team over a season of matches. Data are presented as mean (±SD), median [IQR] and 95th percentile for total impacts per player per-season, resultant linear and rotational acceleration, head impact telemetry severity profile and risk weighted exposure combined probability

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | **Impacts** | **PLA(g)** | | | **PRA (rad/s2)** | | | **HITsp** | | | **RWEcp** | | |
|  | **Range** | **No.** | **Age** | **per-player per-season** | **Mean SD** | **Median [IQR]** | **95%** | **Mean SD** | **Median [IQR]** | **95%** | **Mean SD** | **Median [IQR]** | **95%** | **Mean SD** | **Median [IQR]** | **95%** |
| **Age1234** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | L:< 20 yr. | 7 | 18.7 ±0.8 | 123 ±79 | 17 ±11b | 14 [11-18] | 37 | 2,579 ±2,279bc | 1,863 [1,180-3,071] | 7,705 | 19 ±13c | 16 [14-19] | 35 | 0.0250 ±0.1230bc | 0.0003 [0.0002-0.0011] | 0.0609 |
|  | M:20 - 21 yr. | 7 | 20.4 ±0.5 | 190 ±170 | 17 ±11a | 13 [11-18] | 39 | 2,365 ±2,397ac | 1,519 [1,048-2,642] | 7,157 | 19 ±14 | 16 [14-19] | 39 | 0.0266 ±0.1318ac | 0.0002 [0.0002-0.0008] | 0.0681 |
|  | H: >21 yr. | 9 | 24.0 ±1.5 | 299 ±480 | 17 ±14 | 13 [11-17] | 43 | 2,455 ±2,758ab | 1,457 [861-2,894] | 8,901 | 20 ±17a | 15 [14-19] | 42 | 0.0394 ±0.1654ab | 0.0002 [0.0001-0.0009] | 0.2405 |
| **Height1234** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | L: <1.76 m | 7 | 172.0 ±6.3 | 346 ±534 | 16 ±11bc | 13 [11-16] | 34 | 2,229 ±2,290c | 1,431 [993-2,497] | 6,770 | 18 ±14bc | 15 [14-18] | 34 | 0.0231 ±0.1229c | 0.0002 [0.0001-0.0006] | 0.0437 |
|  | M: 1.76 - 1.87 m | 8 | 183.0 ±2.6 | 137 ±159 | 18 ±13ac | 13 [11-19] | 44 | 2,567±2,757c | 1,588 [903-3,020] | 8,877 | 20 ±16ac | 16 [14-20] | 45 | 0.0400 ±0.1655c | 0.0003 [0.0001-0.0012] | 0.2326 |
|  | H: > 1.87 m | 8 | 189.7 ±2.1 | 153 ±124 | 19 ±13ab | 14 [11-20] | 45 | 2,676 ±2,521ab | 1,873 [1,209-3,073] | 7,808 | 21 ±15ab | 16 [15-21] | 46 | 0.0329 ±0.1447ab | 0.0004 [0.0002-0.0013] | 0.16 |
| **Weight1234** | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | L: <74 kg | 9 | 71.9 ±1.3 | 264 ±488 | 16 ±11bc | 13 [11-16] | 36 | 2,243 ±2,372b | 1,427 [962-2,509] | 6,957 | 19 ±14bc | 15 [14-18] | 38 | 0.0266 ±0.1334bc | 0.0002 [0.0001-0.0006] | 0.0639 |
|  | M: 74 - 78 kg | 6 | 76.5 ±1.4 | 205 ±73 | 18 ±13a | 14 [11-20] | 41 | 2569 ±2,555ac | 1,765 [1,114-2,993 | 7,256 | 21 ±18a | 16 [14-21] | 41 | 0.0307 ±0.1470a | 0.0003 [0.0002-0.0012] | 0.0756 |
|  | H: >78 kg | 8 | 85.3 ±4.5 | 160 ±168 | 18 ±12a | 13 [11-18] | 44 | 2,633 ±2,584b | 1,679 [1,059-3,092] | 8,271 | 20 ±12a | 16 [14-20] | 44 | 0.0351 ±0.1465a | 0.0003 [0.0002-0.0012] | 0.2127 |

[IQR] = Interquartile (25th to 75th) percentile; 95% = 95th percentile; PLA (*g*) = peak linear acceleration in gravitational force (*g*); PRA (rad/s2) = peak rotational acceleration in radians/second2; HITSP = Head Impact Telemetry Severity Profile; RWECP = Risk Weighted Exposure Combined Probability; L = Lower range group; M = Middle range group; H = Higher range group; Significant difference (*p*<0.05) than (a) = lower range group; (b) = middle range group; (c) = higher range group; Significant difference (*p*<0.05) for Friedman repeated measures ANOVA on ranks by (1) = PLA(*g*); (2) = PRA (rad/s2); (3) = HITSP; (4); RWECP